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13. ABSTRACT *(Maximum 200 words)*

The primary result of this project are a clear understanding of the processes which initial cracks in columnar ice under typical conditions. The primary material of study was laboratory-grown freshwater ice, in which the crystals grew as long columns with diameters in the range of a few millimeters. For some fracture toughness measurements we used large single crystals of freshwater ice. Some related work has also been done on laboratory-grown columnar saline ice.

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Modelling & Observation of Crack Nucleation in Ice due to Elastic & Plastic Anisotropy

FINAL REPORT

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JULY 8, 1996

U.S. ARMY RESEARCH OFFICE

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DARTMOUTH COLLEGE

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4 A. STATEMENT OF THE PROBLEM STUDIED

The primary objective of this research project was to understand the process of crack nucleation in polycrystalline ice. Such crack nucleation, or crack initiation, is necessarily the first step in the brittle compressive failure process in which cracks appear in increasing number, grow, and link up with other cracks to form damage zones which lead to failure. An understanding of how the crack nucleation process depends on the external variables of temperature, stress state, and applied strain rate, and the microstructural variables of grain size and shape and crystallographic orientation, is therefore an underlying contribution to a full understanding of the mechanical strength of ice.

4B. SUMMARY OF IMPORTANT RESULTS

The primary result of this project are a clear understanding of the processes which initial cracks in columnar ice under typical conditions. The primary material of study was laboratory-grown freshwater ice, in which the crystals grew as long columns with diameters in the range of a few millimeters. For some fracture toughness measurements we used large single crystals of freshwater ice. Some related work has also been done on laboratory-grown columnar saline ice. We concentrated on the temperature -10° C, which is the temperature most commonly used to study the behavior of freshwater ice. It is also within the range which is experienced in ice engineering applications. We concentrated on an intermediate range of strain rates (of order 10^{-3} to 10^{-2} s^{-1}) at which ice shows generally brittle behavior (at -10°C). We concentrated on uniaxial compressive loading and biaxial compressive loading. For these conditions we achieved the results described below.

First we have been able to show by numerical evaluations of stress concentrations that the mechanism of crack nucleation at grain corners due to elastic anisotropy is unlikely to operate under any conditions. This is because the elastic constants of ice are sufficiently close to isotropic that the strengths of the stress singularities which occur at grain edges (triple junctions) and corners are not sufficiently strong to generate cracking before reaching stresses near the cohesive strength. (Frost & Gupta, 1993; Picu & Gupta, 1996; Picu, Gupta, & Frost, 1994) Some other stress concentration mechanism must operate. The possibilities include dislocation pile-ups, grain boundary sliding, and second-phase inclusions.

Second we have been able to show that decohesion occurs along grain boundaries when they are subjected to stress states with resolved shear components which promote boundary sliding.

(Picu & Gupta, 1995b) This sliding quickly leads to stress concentrations at the edges of the sliding facets, and these ensuing stress concentrations generate cracks. (Picu & Gupta, 1995a; Picu & Gupta, 1995b) Failure occurs when the crack density reaches a sufficient level.

One of the parameters required to model the initiation of crack extensions is the single crystal fracture toughness or work of fracture. To measure this we undertook experiments for measuring crack propagation in single crystals and bicrystals, using the wedge-opening double cantilever beam geometry. (Chernuschenko, 1995) In these experiments the crack opening displacement was measured as a razor blade wedge was inserted into the mouth of a freshly produced crack of known length. From the crack opening and the geometry one can infer the stress intensity factor at which the crack extended. Some measurements of the critical stress intensity factor required for crack propagation were achieved. We discovered, however, that at our relatively slow crack opening rates, the plastic relaxation process within the ice could lead to misleading results. (Chernuschenko, 1995) Another technique for measuring the inherent cohesive strength of ice is the laser spallation experiment reported by Gupta and Tian (Gupta, Argon, Parks, & Cornie, 1992) This experiment is very similar to the interface adhesion technique described in the next paragraph, but it was done on thin single crystals of ice and the spallation process was a decohesion within the ice itself. From it, cohesive strengths on the order of 1.1 GPa were reported for spallation parallel to the basal plane, and 1.3 GPa (at -10°C) and 1.0 GPa (at -40° C) for spallation parallel to prismatic planes.

As a related topic, we have investigated the removal of ice from structures using the laser spallation technique. Paul Archer (Archer, 1996) performed experiments in which thin ice layers were spalled from aluminum substrates. In this technique the reverse side of the aluminum was subjected to a short laser pulses which generated short compressive stress pulses. These pulses propagated through the aluminum substrate and the adherent layer of ice, to reflect off the ice free surface and return through the ice layer as tensile pulses. If the reflected tensile pulses have sufficient magnitude, when they reach the ice--aluminum interface, they can break the interfacial bond and spall the ice away from the aluminum. Measuring the laser pulse magnitude required to produce spallation therefore measures the interfacial cohesive strength. The magnitude of the stresses generated by the laser pulses could be inferred by measuring the time-dependent surface displacements with a laser interferometer.

To evaluate the effect of temperature, spallation experiments were performed using uncoated, unpolished aluminum substrates at -10°, -20°, -30°, and -40° C. (Archer, 1996) To evaluate the effect of coatings, experiments were performed at -10° C on unpolished aluminum, polished

aluminum, and with one micron thick coatings of polyimide and polymethylmethacrylate (PMMA). For all experiments the interfacial strengths were reported as being close to 180 MPa, except for the experiments on unpolished aluminum at -10°C, for which the strength was about 274 MPa. Reports of these experiments will be published in due course.

4 C. PUBLICATIONS.

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V. Gupta, R.C. Picu and H.J. Frost, 1993, "Crack Nucleation Mechanism in Saline Ice", in *Ice Mechanics - 1993* -, edited by J.P. Dempsey, Z.P. Bazant, Y.D.S. Rajapakse, and S. Shyam Sunder, Proceedings of the Ice Mechanics Symposium, First Joint ASCE-EMD, ASME-AMD SES Meeting, June 6-9, 1993, Charlottesville, Virginia, pp. 199-216.

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4 D..SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED

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Vijay Gupta	Co-Principal Investigator
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Chernuschenko, M. A. (1995) Fracture Toughness Measurements in Ice Single Crystals in Double-Cantilever Beam Geometry with the Wedge-Loaded Crack. M.S., Dartmouth College.

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